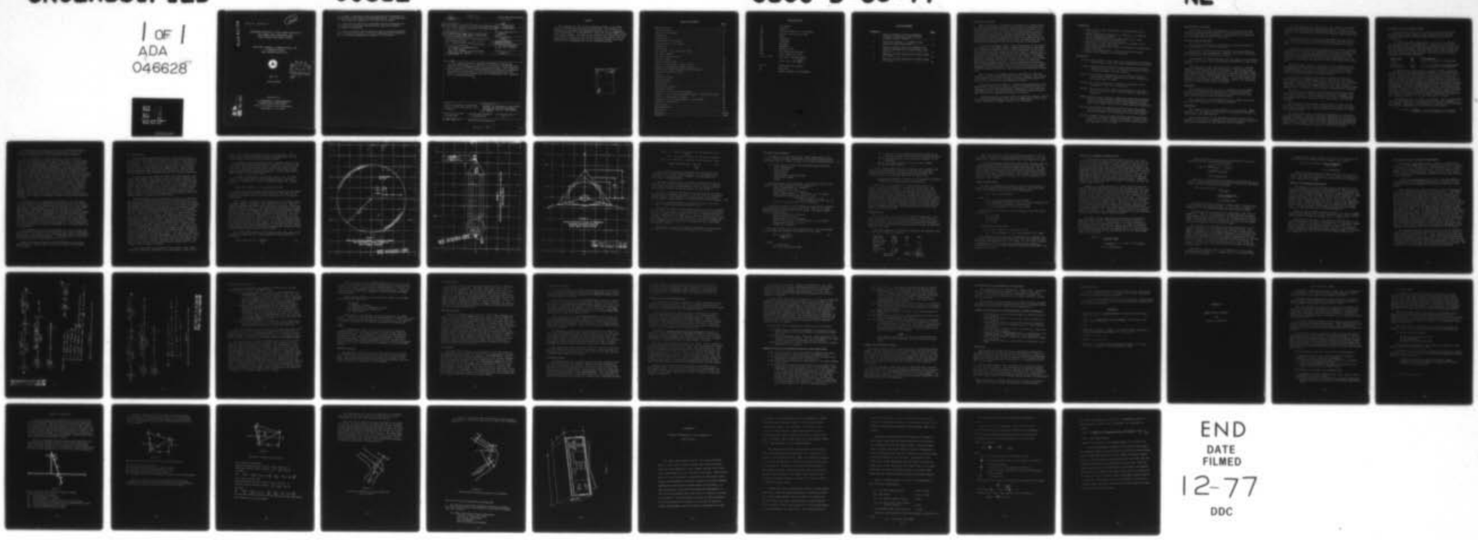

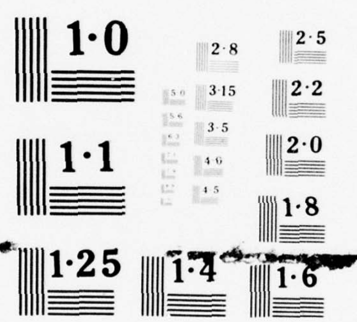
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PERFORMANCE ANALYSIS OF COAST GUARD AN/SPS-64(V) BUOY TENDER RADAR INTEGRATED WITH PRANS MARINE POSITIONING SYSTEM

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JUNE 1977

FINAL REPORT

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15. Supplementary Notes

16. Abstract

This report describes research performed to analyze the expected performance of a system which integrates the AN/SPS-64(V) radar set and the PRANS marine positioning system. The integrated system objective is to provide automatically generated information for maneuvering decisions in buoy positioning operations. The report also contains information and recommendations for implementing the integrated system.

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PREFACE

This research is part of the continuing effort in the Coast Guard to improve buoy positioning operations. The research is conducted to ascertain the expected performance of an integrated system comprised of the AN/SPS-64(V) radar set and the PRANS marine positioning system. Included in the research are preliminary hardware design criteria for interfacing the two sub-systems, cost information for implementation of the integrated system, and recommendations for implementation of the integrated system.

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ABBREVIATIONS

cm	Centimeter
db	Decibel
dbm	Decibel relative to a milliwatt
dbw	Decibel relative to a watt
G	Gain
GHz	Gigahertz
KM	Kilometer
KW	Kilowatt
MHz	Megahertz
N.M.	Nautical mile
PPI	Plan Position Indicator
PRR	Pulse Repetition Rate
r.m.s. error	Root mean square of error $\text{r.m.s. error} = \sqrt{\frac{\Sigma x_i^2}{n}}$
r.p.m.	Revolutions per minute
t_r	Rise time
λ	Lambda, symbol for wavelength

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Purpose of the Study

Numerous methods of improving the operation of placing floating aids to navigation have been, and are being investigated with the objectives of cost reduction and accurate positioning. The present method, involving the use of horizontal sextant angles is a slow and tedious process, limited by environmental conditions, and requiring extensive training for proficiency. Prediction of the accuracy of buoy placement must consider the human factors involved in the angle observations and their interpretation, and any human biases involved, as well as the accuracy of the sextant.

A possible candidate system for the elimination of the sextant angle method is the PRANS system. PRANS was originally developed as a navigation system for use in restricted waters, and employs a mini-computer and high resolution interval timer to analyze radar returns from designated radar targets and determine the position of the vessel relative to the centerline of the channel. The PRANS system has inherent flexibility of application, and can be programmed to provide the position of a vessel relative to some predetermined geographic position. In buoy positioning application, the pre-determined position could be the coordinate for the correct placement of the buoy anchor, and the position of the buoy tender could be computed relative to that position for maneuvering information.

The accuracy of the PRANS system is dependent on radar performance, as well as numerous other factors. However, the accuracy of the PRANS system can be reliably predicted through analysis of these factors and the use of mathematical models.

The purpose of this study is to analyze the performance of the AN/SPS-64(V) radar set in order to obtain a prediction of the accuracy that can be achieved through integration of that radar with the PRANS system. The AN/SPS-64(V) is presently installed aboard both sea-going and coastal buoy tenders in service.

A second objective of this study is to formulate design criteria for interfacing the AN/SPS-64(V) with the PRANS system, and to develop a preliminary hardware design of the interface.

Assumptions

1. Radar does not meet manufacturer's specification due to service life.
2. Routine maintenance schedules are adhered to, in order to assure adequate performance.
3. Radar performance has not degraded below"end of life" criteria as specified by manufacturer.
4. Mean height of radar antennas aboard buoy tenders is approximately 40 feet above water.
5. Ship's mains supply power within requirements of manufacturers specifications.
6. There is no contribution to error by the radar display.
7. Clutter due to weather can be neglected.

Definitions

Scanner: That portion of the radar set consisting of the antenna, driving motor, gears, and rotary transmission line joint.

Clutter: Radar signals returned by radar targets of no specific interest, such as rain, sea return, and objects close to a specified target of major interest.

Radar Cross Section: A measurement of the effective size of a radar target, usually expressed as a ratio relating to one square meter of area.

Transceiver: That portion of the radar set consisting of the transmitter, receiver, and detector.

Display: That portion of the radar set consisting of the Plan Position Indicator (PPI), various controls, and timing functions.

PRANS: A marine vessel position information system which measures the time interval between radar transmitted and received pulses and automatically computes and displays the position of the vessel relative to a known system of coordinates.

Multipath Propagation: A phenomena resulting from flat surface reflection of the radar signals, and causing cancellation and re-inforcement of the amplitude of the radar signal.

X-Band: A segment of the microwave frequency spectrum allocated for marine radar use. (Usually considered to fall in the range of 8-12.5 GHz, and for marine radar specifically in the sub-band of 9.3-9.5 GHz).

Limitations of the Study

The analysis of radar performance will be based on the manufacturer's specifications and end of life criteria, and on test data obtained from the manufacturer. No testing of the radar set will be conducted as a part of this study.

Delimitations of the Study

The effect of multipath propagation of microwave energy will not be considered as a part of this study.

The effect of rain and sea clutter will not be considered in the analysis of radar performance. However, the effect of attenuation due to rain will be taken into account.

The analysis of radar performance will be based on two different sizes of radar target, with corresponding differences in radar cross section.

The analysis of radar performance will be based on a maximum range of 10 nautical miles (18.5 kilometers). This delimitation is based on the average height above water of radar scanners aboard buoy tenders and the economies realized by keeping the radar targets close to the ground. The maximum range is also in keeping with the specified performance of the PRANS system. It should be noted that extension of the maximum range is possible; however, for this study the 18.5 kilometer figure will be employed.

Hypothesis

The AN/SPS-64(V) radar set can be integrated with the PRANS system to provide automatic generation of information for buoy positioning operations, with predictable accuracies better than those achieved with horizontal sextant angles.

The combination of the AN/SPS-64(V) and the PRANS system will facilitate the training of buoy tender personnel.

Methodology

Two different sizes of radar targets will be selected. Their selection will be based on practicality of installation, economy of construction, and configuration.

The characteristics of the AN/SPS-64(V) radar set will be researched, to the level of components as required, to obtain realistic operational parameters for the remainder of the research.

The performance of the radar set will be evaluated in conjunction with the two different radar target sizes at a range of 18.5 kilometers to determine the expected amplitude of the received radar returns. This evaluation will utilize the standard radar range equation.

Characteristics of the radar set that affect the rise time of the received pulse will be analyzed to determine the shape of the pulse at the point where the time interval measurement is actually made.

Data obtained from the above analyses will be used to determine the accuracy of time interval measurements that can be achieved. The accuracy of time interval measurements can be directly related to the accuracy of range determination using the AN/SPS-64(V). The accuracies determined will not reflect the optimum conditions, but rather will incorporate degradation of radar performance with service life.

Using the above results, a prediction will be made as to the overall system accuracy of the combination of the AN/SPS-64(V) with the PRANS system. The data will indicate the accuracy of vessel position determination and will provide a prediction as to the accuracy that can be achieved in buoy positioning.

A preliminary design of the hardware interface between the AN/SPS-64(V) and the PRANS system will be formulated. This design will consider maintenance of the integrity of the radar set of primary importance. Provisions will be included to over-ride any interfacial controls between the PRANS system and the radar controls should immediate use of the radar in its original configuration be required.

The design will be based on two methods of operation: the navigation mode, where the radar operates as originally intended, with all controls operative, and the survey mode, where the PRANS system will control the pulse repetition rate, pulse length, and receiver bandwidth.

The design will also consider alteration of the radar set for improved performance, both in the navigation mode, and in the survey mode, where the survey mode requires improved performance to insure predictable accuracy.

The design effort will also include suggestions for information display and format. Methods of obtaining additional data will be researched to determine the most meaningful information to be displayed. Suggestions for a questionnaire to be distributed among commanding officers of buoy tenders, as well as former commanding officers of buoy tenders, will be presented to effect the final design effort.

Description of the Candidate Radar

The AN/SPS-64(V) radar set is a marine surface search radar which operates in the X-band of radar frequencies at 9.37 GHz (3.200 cm wave length). The peak output power is specified at 20 KW minimum.

The SPS-64 has eight range scales, ½, 1½, 3, 6, 12, 24, 48, and 64 nautical miles corresponding to the perimeter of the PPI. The microwave energy is transmitted in pulses at rates of 3600, 1800, and 900 pulses per second. The duration of the pulses varies with the particular pulse repetition rate (PRR) used. Both the PRR and the pulse duration are controlled by the selection of the range scale per the following schedule:

Range Scale	PRR	Pulse Duration
½, 1½	3600	60×10^{-9} seconds (60 nanoseconds)
3 N.M.		
6, 12 N.M.	1800	500×10^{-9} seconds (500 nanoseconds)
24,48,64 N.M.	900	1×10^{-6} seconds (1 microsecond)

The AN/SPS-64(V) radar employs a Raytheon 167542-1 magnetron as the source of microwave energy. This tube is a frequency tunable device. The radar set incorporates a directional coupler to facilitate performance monitoring and routine testing. A test set is used to measure the ouput power of the magnetron while the radar is in service. No particulars were available as to the accuracy of the test set, but research of commercially available directional couplers, thermocouples, and power meters indicated that a tolerance build-up of approximately 1 db in the measurement of power is a definite possibility. Although the radar output is specified at twenty kilowatts, this study will take into account the possible measurement error of 1 db, and will use the figure of sixteen kilowatts as the radar output. Sixteen kilowatts is 1 db less than twenty kilowatts.

The AN/SPS-64 uses a six foot long antenna. The horizontal beamwidth of the antenna is 1.2 degrees, and the vertical beamwidth is 20.7 degrees. The gain of the antenna is a function of the horizontal and vertical beamwidths with the following relationship:

$$G = 10 \log_{10} \frac{32{,}000}{\text{(product of the two beamwidths in degrees)}} \qquad (1)$$

Theoretically, the antenna gain for the AN/SPS-64 should be 31 db. The manufacturer specifies a minimum gain of 28.5 db, probably accounting for practical manufacturing tolerances.

The noise figure of a radar receiver is used to provide a comparative performance standard for the detection of actual radar returns. The noise figure is primarily dependent on the characteristics of the microwave mixer, and the mixer diodes employed for conversion to the intermediate frequency. The noise present at the mixer, or "front-end" of the radar receiver determines the minimum discernible signal level of the receiver (MDS). The MDS is commonly specified as being three decibels above the noise level. Therefore, the noise level, or noise figure of the receiver has a definite effect on the overall performance of the radar set, both in the detection of radar targets, and the measurement of the range to the radar target. It should be noted at this point that no one parameter in radar can be treated alone, as all parameters interact to affect the performance of the total radar system. Noise figure must be related to the bandwidth of the receiver and intermediate frequency amplifiers before an actual prediction of receiver performance can be made. The noise figure of the AN/SPS-64(V) is specified at 10 db overall (which includes the total receiving subsystem). This figure is comparable to most marine radars operating in X-band.

The transceiver is connected to the scanner with wave guide for transmission of the transmitted energy as well as the received signals. The wave guide employed in the installation has an attenuation factor of approximately 5.9 db per 100 feet of run (for brass wave guide). The manufacturer defines a standard run as being twenty meters (65 feet). Therefore, for the manufacturer's standard run, an attenuation of approximately 3.8 db can be predicted. (If aluminum wave guide is employed,the attenuation factor is reduced slightly). Two things should be noted concerning the wave guide run: the 3.8 db attenuation is present for both the transmitted and the received signals, and must be accounted for in both directions, and no attenuation loss has been considered for wave guide bends and discontinuities.

The scanning rate of the radar antenna is 27 r.p.m. This will vary somewhat with relative wind velocities and other environmental factors (ie., ice build-up, etc.) The rotational speed of the scanner is designed to match the persistence of the PPI scope, and for most marine radars falls in the range of 25-35 r.p.m.

Additional characteristics of the AN/SPS-64(V) will be discussed below as they are used to define the expected performance of the radar.

The Radar Target

In most radar applications, the size of the radar target is not defined. The target size is directly related to the expected performance of the radar set, however, and must be considered in the analysis. If the size of the radar target can be controlled, the target can be considered as an integral part of the overall system. This is the case with the PRANS system. Radar targets are installed at known locations specifically for use with the system, and their size and configuration are therefore controlled.

A radar target can assume any number of configurations, both simple and complex. Most radar targets of complex configuration can be broken down to combinations of flat plates, cylinders, and spheres. The effectiveness of the target as a reflector of radar energy back to the antenna is a function of the alignment of the target with the incident energy as well as the size and configuration. Figure 1 indicates the relative physical size of a flat plate, a cylinder, and a sphere with equivalent effectiveness as radar targets. It is easily observed that the sphere is the worst target, and the cylinder is not much better.

Several methods have been developed to enhance the effectiveness of radar targets without going to extremes of physical size. The enhancement is related to the ability of the target to reflect the energy impinged on it directly back to the source of the energy. The Luneberg lens achieves this objective by a refractive process through layers of different dielectric materials. The incident wave is focused by the refraction process to a point on the "rear" wall of a sphere (see figure 2). The energy is then reflected back from the rear wall, through the refractive dielectric layers, and exits the sphere as a plane wave in the opposite direction from where it entered the sphere. The smaller sizes of Luneberg lens reflectors are useful in environments where there is little or no clutter, and their primary application is to improve the ability to detect small targets (ie., life rafts, small air craft, etc.) The Luneberg lens reflector can be used in the proposed application with the RM-1220/6XR and the PRANS system. In order to achieve the required target size, however, this type of reflector becomes uneconomical and extremely heavy. In comparison with other types of reflectors used with the PRANS system in the past, a Luneberg lens reflector of equivalent radar cross section would be a sphere 48 inches in diameter, weighing more than 650 pounds. The cost of such a device, as received from one manufacturer, is estimated to be in excess of $9,000.

A practical form of the enhanced radar target is the corner reflector. These are configured by two orthogonal planes, the di-

hedral, and by three orthogonal planes, the trihedral. The dihedral has limited application due to the minimal field of view in one plane, and will not be discussed further.

A trihedral reflector employed with an X-band radar set, and constructed from three square sheets, 40 inches on a side, is the equivalent of flat plane radar target, square in shape, 630 feet on a side. Therefore, three planes, with a total area of three square meters can be configured to present a radar target equivalent to almost 37,000 square meters.

In order to express the radar cross section (ie., the efficiency) of a radar target in more manageable terms, the cross section is referred to in terms of decibels relative to a square meter:

$$\text{Radar Cross Section} = 10 \log_{10}(\text{meters square})$$

In the case of the 37,000 square meters noted above, the Radar Cross Section would be equal to 45.7 db re m^2. This form of expression is readily used in the radar range equation, as will be shown later.

The trihedral reflector can be constructed of different shapes of planes: square, triangular, and sectors of a circle. The relationship between the radar cross section to the size of the three types is shown in Figure 3. The square sided reflector is the most physically compact, holding the radar cross section constant among the three types. The reflector configured from sectors of a circle has the disadvantage of wasting material in manufacture, and will not be discussed further. Depending on the requirement for radar cross section, either the square or the triangular sided reflectors are viable candidates for application. For a given dimension along the intersection of two of the planes, the triangular sided version has a radar cross section approximately 9.5 db less than the square sided version, but has the advantage in manufacture of getting twice as many planes from one piece of sheet metal.

For the trihedral reflector with square sides, the radar cross section (in square meters) is determined from the following relationship:

$$\text{Radar cross section} = \frac{12\pi\, a^4}{\lambda^2} \tag{2}$$

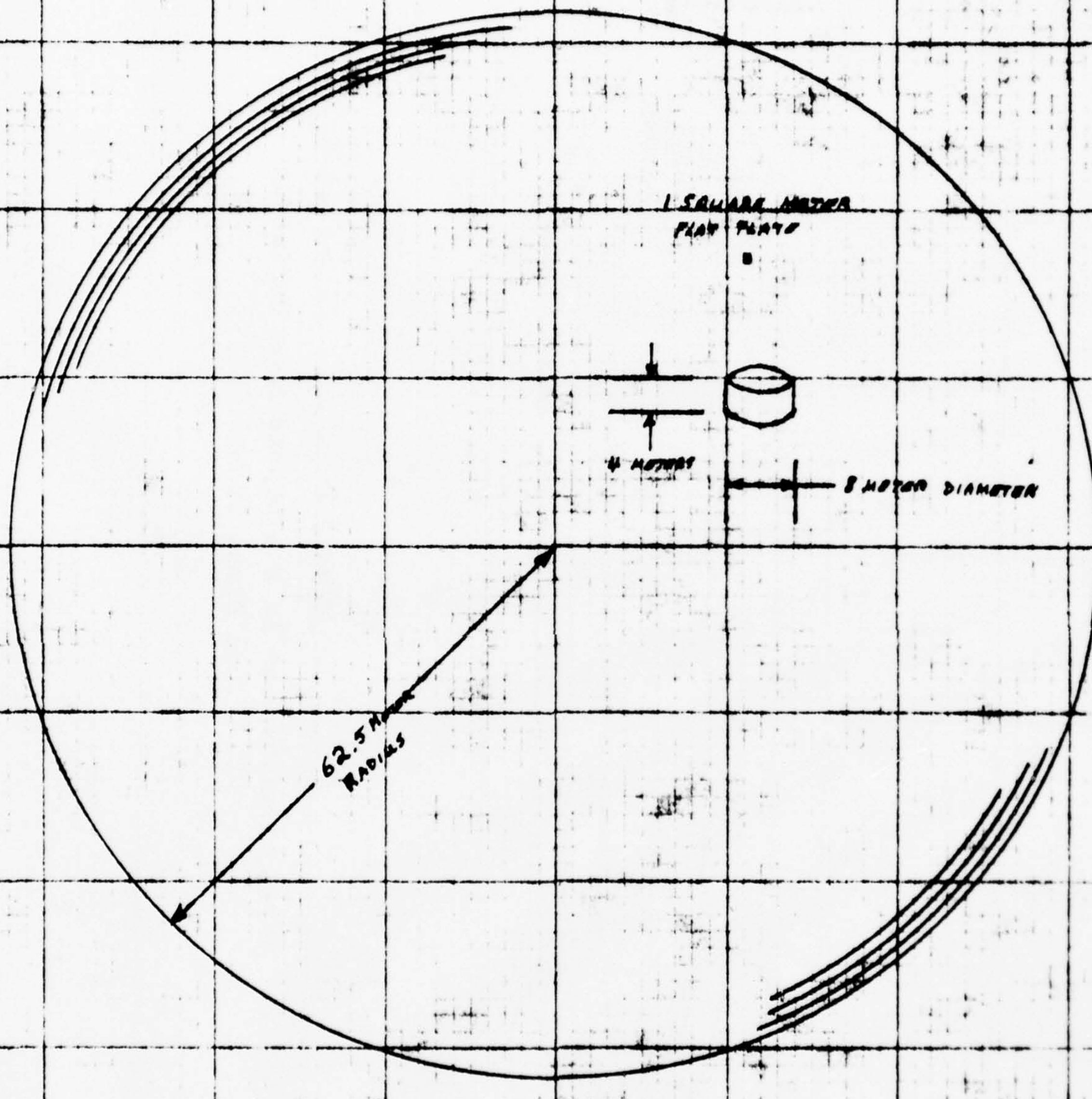

Figure 1

Relative Physical Sizes of Different Shapes
With Equivalent Effectiveness as
Radar Targets (X-Band)

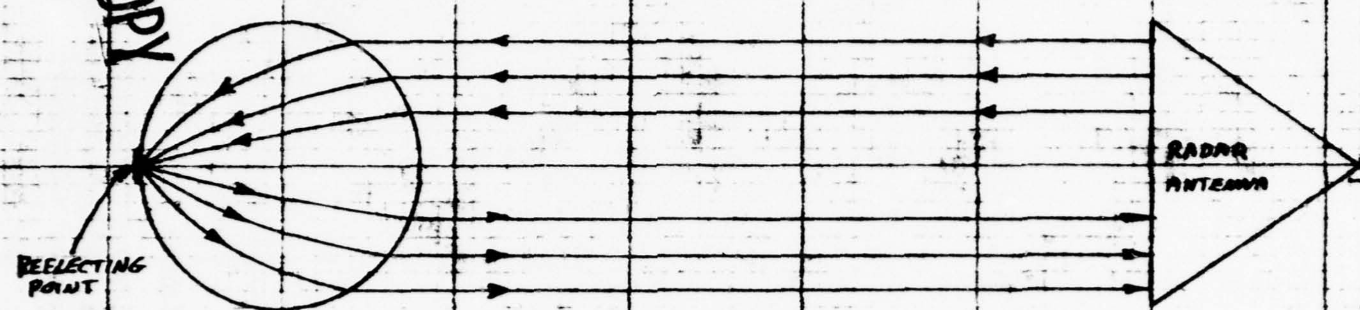

Figure 2

Refraction Process in a Luneberg Lens Reflector
(One Plane Shown)

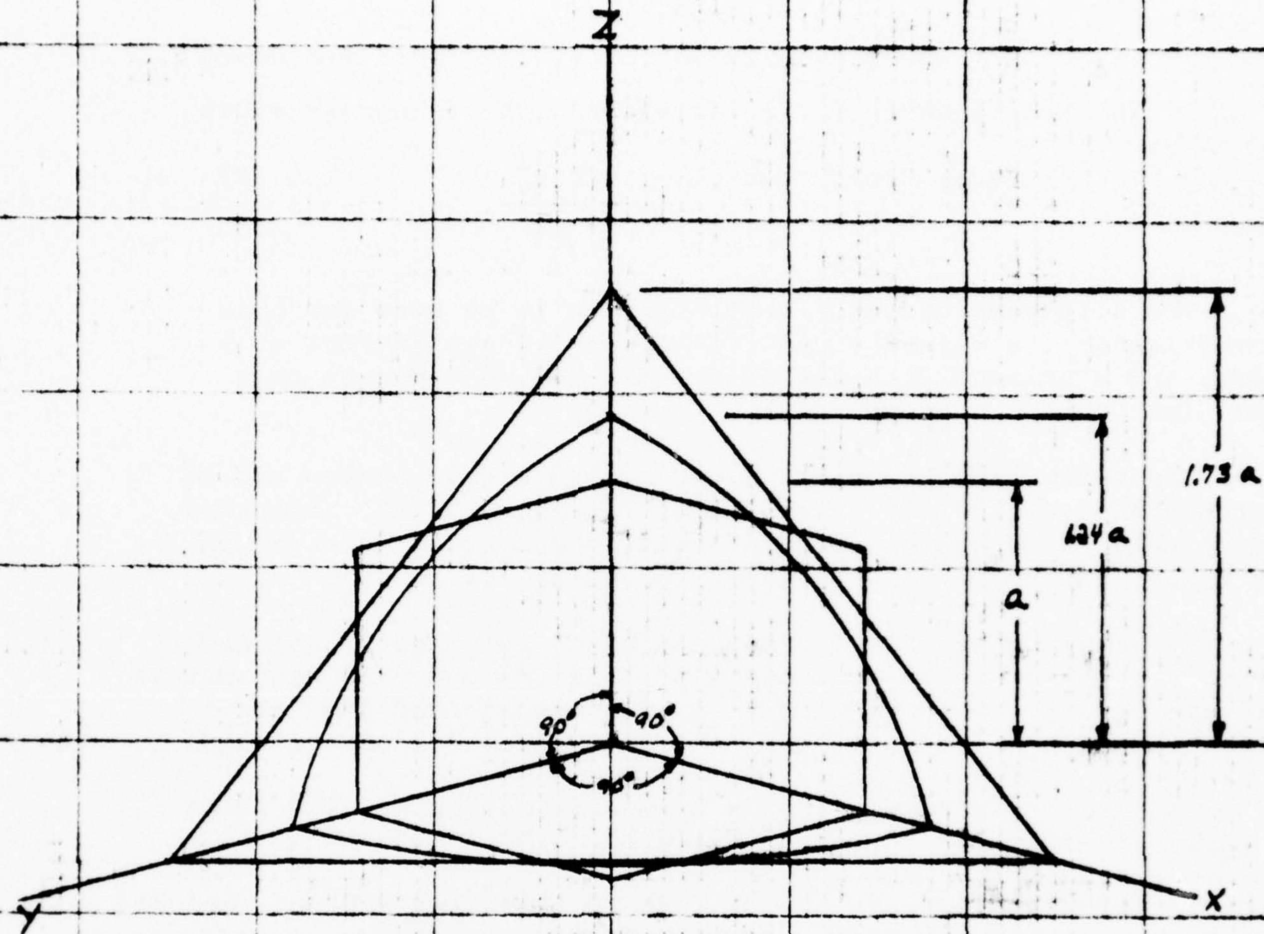

Figure 3

Relative Physical Sizes of Different
Trihedral Configurations of
Equal Radar Cross Section

where: a = length in meters of the intersection of two planes

λ = wavelength in meters of the radar frequency

The relationship for a reflector with triangular sides is:

$$\text{Radar Cross Section} = \frac{4\pi a^4}{3\lambda^2} \qquad (3)$$

Two different trihedral reflectors will be used for this investigation, a square sided trihedral, 100 centimeters on a side, and a triangular sided trihedral, 100 centimeters on a side (not on the hypotenuse).

The radar cross section of the square sided version can be calculated to be 36,815 square meters, or 45.7 db/m^2. Likewise, the 1 meter triangular sided reflector radar cross section can be calculated to be 4,090 square meters, or 36.1 db/m^2.

In order to account for manufacturing tolerances, the radar cross section is normally reduced by 1 db for every 30 centimeters of side length. This results in a cross section of 42.9 db/m^2 for the square sided reflector, and 32.8 db/m^2 for the triangular. (4)

The cost of manufacturing a trihedral reflector, 100 cm on a side, is estimated to be approximately $100.

Although the effects of multipath propagation are not included in this study, it should be noted that as an adjunct to the development of the PRANS system, Associated Controls & Communications, Inc., of Lynn, Massachusetts has developed a computer program for the installation heights of the radar reflectors. Using the heights above water generated by this program results in continuous performance of the PRANS system without loss of information due to multipath propagation effects.

Information concerning the system performance in the presence of radar clutter is contained in Appendix B of this report.

The Radar Range Equation

"Perhaps the single most useful simple description of the factors influencing radar performance is the radar equation which gives the range of a radar in terms of the radar characteristics." (5)

The radar equation relates the following characteristics:

Power Transmitted
Power Received
Antenna Gain
Wave Length
Radar Cross Section of Target
Propagation losses
Range

For application in this analysis, the following will be considered as entering arguments for the equation:

Power Transmitted: 16 kilowatts
Antenna Gain: 28.5 db
Wave Length: 3.2×10^{-2} meters
Radar Cross Section: (1) 42.4 db/m^2, (2) 32.8 db/m^2
Propagation Losses: Wave guide, 7.6 db
Rainfall (6 mm/hr), 3.0 db
Total Propagation loss: 10.6 db
Range: 10 nautical miles (18.5 kilometers)

To facilitate the use of the equation, the entering arguments are expressed in decibels, with power as db relative to a watt, linear dimensions as db relative to a meter. The above characteristics then become:

Power Transmitted: 42 db/watt
Antenna Gain: 28.5 db
Wave Length: (-) 29.8 db/meter
Radar Cross Section: (1) 42.4 db/m^2, (2) 32.8 db/m^2
Propagation Losses: -10.6 db
Range: 42.7 db/meter

The radar equation can take numerous forms. For the purpose of this study, the following relationship will be used:

$$R^4 = \frac{P_t \, G_t{}^2 \, \lambda^2 \sigma}{(4\pi)^3 \, P_r} \qquad (6)$$

where:

R is the range
P_t is the transmitted power

G_t is the gain of the transmitting antenna (squared because it is also the gain of the receiving antenna)

λ is the wave length of the microwave frequency of the magnetron

σ is the radar cross section of the radar target

P_r is the received power

In this investigation P_r is the unknown, and the other parameters have been defined. Because of the use of logarithms, through the conversion of the parameters to db relative to a particular unit, the equation takes the following form:

$$P_r \text{ (db/watt)} = P_t \text{(db/watt)} + (2) \text{ Gain of antenna(db)} - (2)\lambda \text{ (db/m)} + \sigma(\text{db/m}^2) - (3)(10)\log_{10}(4\pi) - (4)\text{Range (db/m)}$$

This form of the equation is a very workable device for analysis of radar performance. In addition to the above parameters, propagation losses, both within and without the radar system can be easily included. For purposes of this study, the internal losses will be limited to the attenuation of the wave guide run, 7.6 db total (including transmit path and receive path), and the external loss factor will be limited to attenuation due to rainfall (rate of precipitation taken to be 6 mm per hour) amounting to 3.0 db for the total propagation path of twice the range of 18.5 kilometers.(7) These attenuation factors are lumped into one term for propagation losses, and subtracted from the right hand side of the above equation.

Received Power

The first step in the analysis of radar performance for this study is to determine the level of the received power under the given conditions. Once this is accomplished, the ranging accuracy can be determined through analysis of the intermediate frequency amplifiers and video detector characteristics, as well as the noise figure of the mixer.

The radar equation is utilized to calculate the expected level of the received power as follows:

Parameter	Value	+db	-db
Power (P)	16KW	42	
Antenna-Gain	28.5db	57	
Wave Length	3.2cm		29.8
Target (σ)	(1)	42.4	
$(4\pi)^3$			33.0
Propagation	10.6db		10.6
Range	18.5KM		170.7
Sub-totals		141.4	244.1
Resultant			-102.7db

This indicates that, using a square sided reflector, 100 cm on a side, the received signal power should be equal to -102.7 db relative to a watt, or -72.7db relative to a milliwatt (-72.7 dbm).

A 9.6 db difference between the square sided reflector and the triangular sided reflector was determined earlier, with the triangular sided being 9.6 db less in radar cross section. All that is necessary to determine the received power using the triangular sided reflector is to account for the 9.6 db difference by reducing the result above by that amount. This yields a received power level of -112.3 db relative to a watt, or -82.3 db relative to a milliwatt (-82.3 dbm).

Signal-to-Noise Ratio

In order to determine the signal-to-noise ratio,the level of noise in the receiver must first be determined. The noise power P_n can be determined from the following relationship:

$$P_n = (N.F.) \times (k) \times (T_o) \times (B)$$

where:

N.F. is the noise figure of the receiver
k is Boltzmann's Constant (1.38×10^{-23} watt-sec/Degree K)
T_o is 290^o Kelvin (reference temperature)
B is the bandwidth of the receiver 24 MHz

When expressed in decibels, these parameters have the following values:

N.F.: 8.8 db
k: -228.6 db
T_o: 24.6 db
B: 73.8 db

Using these values yields:

$$P_n = 8.8 \text{ db} - 228.6 \text{ db} + 24.6 \text{ db} + 73.8 \text{ db}$$

$$P_n = -121.4 \text{ db/watt, or } -91.4 \text{ db/milliwatt } (-91.4 \text{ dbm})$$

The signal-to-noise ratio can be determined by comparing the received signal power to the noise power. For the condition using the square sided reflector: P_r= -72.7 dbm, P_n= -91.4 dbm, yielding a difference of 18.7 db. For the triangular sided reflector: P_r= -82.3 dbm, P_n= -91.4 dbm, yielding a signal-to-noise under that condition of 9.1 db.

Error in Measurement of Time Interval

In measuring the time interval between pulses, the prime factor that must be considered is where on the pulse the time of arrival is to be determined. Several methods are employed to define the arrival time, with the stipulation that the same point on each and every pulse must be used for consistent results. One such method determines the times at which the leading and trailing edges of a pulse cross a pre-determined threshold level, and establishes the mean of the two times as the time of arrival. Another method defines arrival time as the time that the leading edge alone crosses a pre-determined threshold level. These two methods are usually referred to as center of gravity tracking and leading edge tracking.

Because, in a radar application, signal level fluctuations can be expected, some means of moving the threshold level to compensate for variations in amplitude should be employed. One such method, called constant fraction of pulse height, senses the amplitude of the pulse and automatically sets the threshold level to yield consistent results from one pulse to the next. Circuits developed for nuclear instrumentation have the ability to determine the same point on each pulse with a range walk of less than 200 picoseconds at 100:1 dynamic range. This device, usually referred to as a constant fraction discriminator, has been designed and utilized in several radar and laser systems by Associated Controls and Communications, Inc. Since this device works on the leading edge of the pulse, it is important to determine the characteristics of the pulse at the point of discrimination.

If pulses could be generated and received with infinitely fast rise times ($t_r = 0$), there would be no error involved in measuring time interval. Unfortunately, the ideal situation is not present with the AN/SPS-64(V) radar. In order to determine the accuracy of the time interval measurement, the rise time of the transmitted pulse must be considered, as well as what degradation to the rise time can be anticipated due to the finite bandwidth of the receiver.

$$t_{r(\text{rec.})} = \frac{1}{\text{Bandwidth (MHz)}}$$

$$= \frac{1}{24 \times 10^6} = 4.166 \times 10^{-8} \text{ seconds}$$

$$= 41.66 \text{ nanoseconds}$$

The rise time of the pulse at the discriminator can be determined from the following relationship:

$$t_{r(Disc.)} = \sqrt{t^2_{r(trans.)} + t^2_{r(rec.)}}$$

$$= \sqrt{(10)^2 + (41.66)^2}$$

$$= 42.84 \text{ nanoseconds}$$

The error in time interval measurement incorporates the rise time at the discriminator with the signal-to-noise ratio determined earlier using the following relationship:

$$\text{Time interval error} = \frac{t_r}{(2 \times S/N)^{\frac{1}{2}}}$$

$$= \frac{42.84 \text{ nanoseconds}}{(2 \times 74.13)^{\frac{1}{2}}}$$

$$= 3.518 \text{ nanoseconds}$$

Converting from time interval to range yields a ranging error of 41.6 inches over the total path, or 20.8 inches in range determination of the distance between the radar and the target.

The above error is indicative of a measurement made with one pulse pair. That is, the measurement is made between one transmitted pulse and one received pulse. The ranging error can be reduced (actually the signal-to-noise ratio is improved) by a factor equal to the square root of the number of returns from the target in use as the antenna scans across the target.

The trihedral corner reflector can be considered as a point source. Therefore, as the antenna beam scans the target, the number of returns (ie., the sample size for time interval measurement) is dependent on the horizontal beamwidth of the antenna, the pulse repetition rate of the radar, and the scanning rate of the antenna. The AN/SPS-64(V) has a horizontal beamwidth of 1.2 degrees, and a scan rate of 33 rpm, and therefore scans one beamwidth in 6×10^{-3} seconds. At a pulse repetition rate of 3600 pulses per second, this indicates that there should be 21 pulses to integrate for each scan.

Dividing the ranging error by the square root of 21 yields an approximation of the r.m.s. ranging error of 4.6 inches (using the larger radar target.)

Applying the lesser signal-to-noise ratio obtained with the triangular sided reflector yields a larger r.m.s. error.

$$\text{Time interval error} = \frac{42.84 \text{ nanoseconds}}{(2 \times 8.13)^{\frac{1}{2}}}$$

$$= 10.63 \text{ nanoseconds}$$

Converting time interval to range yields an error of 125.5 inches total over the entire path, or 62.7 inches in range to the target. Dividing this figure by the square root of 21 yields an r.m.s. error of 13.7 inches.

Summary of Performance Expectations

The analysis thus far has shown that the AN/SPS-64(V) radar can be utilized for accurate range measurements. The accuracy is dependent upon numerous factors that affect radar performance. The analysis has been made using two different radar targets at a range of ten nautical miles (18.5 KM). The two radar targets are trihedral configured, one with square sides, 100 cm on a side, the other having triangular sides, 100 cm on a side, with a hypotenuse of 141.4 cm. It was demonstrated that the square sided reflector is the better of the two targets, its use resulting in a higher level of received power, a corresponding higher signal-to-noise ratio, and improved accuracy in range measurement.

Using the square sided reflector resulted in an r.m.s. ranging error of less than five (5) inches, while the use of the triangular sided reflector yielded an accuracy of 13.7 inches r.m.s.

Examination of the radar range equation indicates that as the range is decreased, the level of received power is increased. Therefore, the result of decreasing the range to the target is to improve the ability to accurately measure the range. For example, if the triangular sided reflector were used at a range of 6 nautical miles (11 KM), the ranging error would be reduced from 13.7 to 5.0 inches r.m.s.

Preliminary Design Criteria for Performance

The proposed integrated system, including the AN/SPS-64(V) radar set and the PRANS system, is specified to achieve a positional accuracy of five (5) feet r.m.s. error maximum at the maximum range of ten nautical miles (18.5 KM). Previous analysis of the PRANS system has indicated that a ranging error of five inches r.m.s. maximum must be achieved in order to satisfy this positional specification.

It has been demonstrated that the five inch requirement can be satisfied using the AN/SPS-64(V) radar in conjunction with a trihedral reflector comprised of three planes, each one a meter square.

The equations of the total derivatives used to determine the five inch requirement are shown in Figures 4 and 5. The PRANS system generates positional information in X/Y coordinates, with the Y axis normally representing the centerline of the channel, and the X axis representing lateral offset from the centerline. The two axes can be programmed to represent lines other than the centerline of the channel, with the Y axis as either a line parallel to the centerline of the channel, but offset some distance from it, or a line that intersects the centerline of the channel at some pre-determined angle. In the PRANS system, the X axis is always orthogonal to the Y axis. In the equations of the total derivative, the error measured along the X axis is defined as dh, and the error measured along the Y axis is defined as dR. The origin of the X/Y coordinate system is usually considered to be the intersection of the channel centerline with the centerline of the next channel. The origin can be programmed to represent some other point. In this proposed application, such a point might be the desired position of a buoy sinker, and the Y axis could be programmed to pass through that point parallel with the centerline of the channel.

The equations shown in Figures 4 and 5 are for the PRANS system as originally designed, and reflect the use of two range determinations to derive position. In the proposed system, one additional range determination will be made. The three range measurements will permit the determination of three position observations, one from each combination of two range measurements. This will serve to improve the overall positional accuracy of the total system. The magnitude of the improvement has not yet been determined.

$$dh = \left[\frac{j}{s}\cos\alpha - \frac{j\left(1 - \frac{j^2-g^2}{s^2}\right)\sin\alpha}{2f(x)}\right]dj - \left[\frac{g}{s}\cos\alpha + \frac{g\left(1 + \frac{j^2-g^2}{s^2}\right)\sin\alpha}{2f(x)}\right]dg$$

$$+ \left[\frac{j^2-g^2}{4s^2}\cos\alpha + \frac{\left(\left(\frac{s}{2}\right) - \left(\frac{j^2-g^2}{s}\right)\left(\frac{j^2-g^2}{2s^2}\right)^2\right)\sin\alpha}{2f(x)}\right] - \cos\alpha \, dD$$

$$- \left[\frac{j^2-g^2}{2s}\sin\alpha - D\sin\alpha + (\cos\alpha)f(x)\right]d\alpha$$

where: dh is error along x axis

j is distance to target j

g is distance to target g

s is distance between targets

α is angle between line $\overline{jg}$ and channel center line

D is distance from midpoint of line $\overline{jg}$ to channel centerline

$$f(x) = \left[\frac{j^2+g^2}{2} - \frac{s^2}{4} - \left(\frac{j^2-g^2}{2s}\right)^2\right]^{1/2}$$

Figure 4.
Equation of Total Derivative of Error Along the X Axis

$$dR = \left[\frac{j}{s}\cos\alpha + \frac{j\left(1 - \frac{j^2 - g^2}{s^2}\right)\cos\alpha}{2f(x)}\right]dj - \left[\frac{g}{s}\cos\alpha - \frac{g\left(1 + \frac{j^2 - g^2}{s^2}\right)\cos\alpha}{2f(x)}\right]dg$$

$$+ \left[\frac{j^2 - g^2}{4s^2}\cos\alpha - \frac{\left(\frac{s}{2} - \left(\frac{j^2 - g^2}{s}\right)\left(\frac{j^2 - g^2}{2s^2}\right)^2\right)\cos\alpha}{2f(x)}\right]ds - (\sin\alpha)\,dD + dk$$

$$- \left[\frac{j^2 - g^2}{2s}\sin\alpha + (\sin\alpha)f(x) + D\cos\alpha\right]d\alpha$$

Where: dR is error along Y axis

j, g, s, D, and α are as shown in Figure 4

k is an offset distance along the Y axis

$f(x)$ is as shown in Figure 4

Figure 5.
Equation of Total Derivative of Error Along the Y Axis.

Functional Design Criteria

Several restrictions were placed on integration of the AN/SPS-64(V) radar set with the PRANS system:

1. Two operational modes were defined as NAVIGATION MODE and SURVEYING MODE. In the first mode,the radar will function as originally intended, with all controls functional, and no degradation to performance. In the SURVEYING MODE, the PRANS system will control such functions as are necessary to assure overall system performance.
2. A simple and direct means shall be provided for switching between the NAVIGATION MODE and the SURVEYING MODE. This means should involve no more than operation of a single switch. As an adjunct to this provision, some indication should be provided at the radar PPI console to indicate that the SURVEYING MODE is in use, and likewise, at the PRANS display console, some indication that the NAVIGATION MODE is in use.
3. Only one radar antenna will be employed. This restriction does not preclude the use of an antenna different from that presently installed as part of the radar set.

One other delimitation was placed on the interface design, that the radar set need not function as a navigation radar when the integrated system was in the SURVEYING MODE. It is considered advantageous, however, to design the interface circuits to provide as much use as possible of the radar presentation during the SURVEYING MODE.

It was cited earlier that the PRANS system requires the shortest pulse duration and the most frequent pulse repetition rate in order to assure satisfactory performance. The AN/SPS-64(V) radar uses the short pulse duration at the PRR of 3600 pulses per second on range scales of three miles and under. Therefore, the radar set and the PRANS system have compatible requirements at ranges of three miles and under. The theoretical maximum range of a radar set operating at a PRR of 3600 pulses per second is 22.5 nautical miles. This is based on the period between pulses and the transit time of the microwave energy. With the PRR being the only constraint, the radar could present a PPI display on range scales as high as twelve nautical miles. It should be noted, however, that the PPI presentation will not be as brilliant on the longer ranges (above three nautical miles) due to the shorter pulse duration, and the probability of detection of targets at the longer ranges will be reduced.

While operating in the SURVEYING MODE,the PPI will also have a spot in the center of the screen representing the outgoing pulse. This is the result of detecting the outgoing pulse to initiate the time interval measurement, and will be discussed later. The sea-clutter control may also be somewhat inhibited during the SURVEY MODE operation.

The following functions are required as inputs to the PRANS system from the radar set:

(1) Video
(2) Modulator trigger
(3) Outgoing pulse (magnetron firing)
(4) Antenna position indication
(5) Stern marker

Additionally, a gyrocompass input is required by the PRANS system. Because of the fact that the AN/SPS-64(V) is a North stabilized unit, interface with the gyrocompass can be achieved in the radar set in order to economize on the cabling requirements of the system.

Video

The AN/SPS-64(V) radar in the wide band position provides 28 MHz bandwidth at the output of the I.F. input stage following the balanced mixer. This bandwidth is suitable for satisfactory processing of the reflected signal without excessive degradation to the pulse shape. A properly designed take-off at this point into a separate intermediate frequency amplifier, detector and video amplifier is easily implemented and is presently part of the PRANS system.

Modulator Trigger

The modulator trigger is used to "arm" several circuits within the PRANS system in preparation for the time interval measurement. Some finite time delay exists between the trigger and the actual emission of the microwave pulse from the magnetron, and this delay is employed to enable the timing sequence.

Outgoing Pulse

In order to make a time interval measurement, both a START and a STOP signal are required. The STOP signal is derived from the detected video output of the receiver. The START signal must be derived from the magnetron pulse, either by sampling the magnetron current, or by detecting the small amount of microwave energy that leaks past the TR cell. The second method is preferable as both the START and STOP signals are subjected to the same delays through the radar receiver, thereby enhancing the ranging accuracy. In the PRANS system, the modulator trigger is used to identify the outgoing pulse in this second method as both the START and STOP signals exit the receiver from the same port.

Antenna Position

A means of determining the position of the radar antenna as it scans is required by the PRANS system in order to accept START and STOP signals only from the correct radar target. The time interval counter is gated to make measurements only when the radar beam scans across the targets of interest. In order to achieve this function, the position of the antenna must be resolved to very small increments of angle. The AN/SPS-64 employs a synchro resolver to cause the trace on the PPI to sweep in synchronization with the antenna. A synchro resolver does not provide the kind of resolution or repeatability that is required for this application. An optical shaft encoder must be directly coupled, through suitable gearing, to the antenna. Optical shaft encoders are available in synchro housings which are easily installed in most radars, and are available in angular increments small enough to provide resolution of antenna position down to one minute of arc.

Stern Marker

The PRANS system requires an indication of when the antenna is facing directly aft in order to initialize the measurement process, and control functions within the system. The AN/SPS-64(V) has provisions for the use of a stern marker switch in the scanner assembly, and this should be suitable for this application. Should the stern marker already be employed (ie., in the NAVIGATION MODE), provisions can be made to use it for PRANS without degradation. In most radar installations a radar shadow exists over the stern, caused by the mast or funnel of the vessel. Since the stern mark would fall within this shadow it is considered to be advantageous over the heading mark which falls ahead of the vessel, and could possibly prevent detection of a target on the PPI which lies directly ahead.

Interfacial Controls

As cited earlier, one of the restrictions placed on the design of the interface between the radar set and PRANS was that a simple and direct method of switching between the NAVIGATION MODE and the SURVEYING MODE be provided.

When this switch is in the NAVIGATION MODE position, all radar controls will be operational at the radar console, and an indication shall be provided at the PRANS display console to signify that the radar is not under the control of the PRANS system, and that any data presented on the PRANS display is not valid. (The PRANS display could be blanked when the switch is in the NAVIGATION MODE to preclude the use of erroneous data).

When the switch is in the SURVEYING MODE position, control of the pulse duration and the pulse repetition rate will be governed by the PRANS system, and held constant at 60 nanoseconds and 3600 pulses per second regardless of the position of the range selector switch on the radar console. This function can be provided through the use of relays.

In addition to controlling the pulse duration and repetition rate, the STC (sensitivity time control) function in the radar must be slightly inhibited in order to detect the outgoing pulse. The receiver STC serves to reduce the gain of the receiver front end for a short period of time during the outgoing pulse, and gradually restores the gain of that stage as a function of time to prevent overloading of the receiver by returns from close radar targets.

The inhibition of the STC function will be gated to occur only when the radar beam scans a target of interest, thus reducing the brightness of the resultant spot in the center of the PPI, and preventing phosphor burn at that point.

Confidence Factor

The PRANS system has internal range and bearing brackets which are used to gate the time interval counter to accept information only from the targets of interest. In previous applications, these brackets have been displayed on the PPI of the radar to assure the correct operation of the system. This measure provides a confidence factor during operations in the SURVEYING MODE. With knowledge of the approximate location of the radar reflectors, the operators can judge the operation of the system by observing the displayed brackets

in relationship to the PPI presentation of land masses in the vicinity, and can determine that the brackets do, in fact, surround the targets of interest. This procedure is not required for operation in the SURVEYING MODE, and is only suggested as a confidence factor. Provisions for this feature are easily implemented.

Operation of the Integrated System

One parameter that must be addressed in buoy positioning is the desired position of the buoy. The List of Lights specifies buoy position in latitude and longitude coordinates of degrees and minutes, with the minutes carried out to one decimal place.

Since the majority of floating aids to navigation are used to mark the extremities of shipping channels, it is interesting to note that the U.S. Army Corps of Engineers uses the state plane coordinate system in dredging these same channels. Conversion between the latitude/longitude and the state plane coordinate systems is possible, but what must be considered in this case is the possibility of error in the conversion process, as well as human bias in picking the coordinates from a chart or map.

According to Dutton's Navigation and Piloting, the implied accuracy of a latitude coordinate expressed in degrees, minutes and tenths of minutes, indicates the coordinate is accurate to the nearest tenth of a minute.[7] The coordinates given in the List of Lights, therefore, are assumed accurate to approximately 300 feet.

The state plane coordinate system is a "local" system, measured in feet along X and Y axes with the origin of the coordinates located within the borders of a particular state. The coordinates of a particular geographic point are carried out to two decimal places, implying accuracy of 1/100th of a foot. It is easily recognized that a geographic position, such as the desired position of a buoy, can be more definitively specified in this coordinate system. This fact, coupled with the fact that the channel is dredged and maintained in the state plane system, enhances the recommendation that the state plane system be used to specify the desired position of buoy anchors.

Assuming that the desired buoy position is specified in the state plane system, the position coordinates can be programmed into the PRANS computer, and thereafter the particular buoy can be referred to by the light number from the List of Lights, or some other suitable designation.

Given the buoy position, channel characteristics, and radar target positions in a common coordinate system, all can be mathematically related to generate the position of the buoy tender relative to the desired buoy anchor position, or to the intersection of the channel centerline and the centerline of the next channel in sequence.

Another factor that must be accounted for in using the integrated system is the distance from the bridge of the buoy tender to the port and starboard chain stoppers. This offset from the conning station to the chain stoppers must be considered in the maneuvering decisions of the conning officer in buoy positioning operations. In the integrated system, the offsets from the conning station to each of the chain stoppers can be programmed into the computer, and automatically accounted for in the generation of positional information by the PRANS system. The information thus generated can be used to position the chain stopper in use directly over the desired position of the buoy anchor, without the need of mentally accounting for the offset.

For purposes of this example the following will be assumed:

1. The PRANS computer has been programmed to coordinate system which places the X/Y axes through the desired buoy anchor position.
2. The channel parameters (ie., the point, slope equation of the centerline of the channel, and the coordinates of the radar targets) are correctly entered into the program.
3. The buoy coordinates in state plane system have been correctly entered into the program.

Example of Use of the Integrated System in Buoy Positioning

1. The conning officer enters the channel designation by means of a calculator type keyboard on the PRANS console.
2. The Conning officer enters the designation of the buoy to be positioned by means of the same keyboard.
3. The Conning officer enters the designation of the chain stopper to be used.
4. The system is prepared for initialization by determining the coordinates of some arbitrary point in the channel. These coordinates can be referenced to the end of the channel (ie., 10,000 feet from the intersection of the centerline of the channel and the centerline of the next channel. If the least width of the channel is 600' or less, the system will assume that the buoy tender is within plus or minus 300 feet of the centerline. Should a wider channel be encountered, the coordinate of offset from the center of the channel will also be a required entry.

6. When the vessel reaches the pre-determined point the conning officer presses the START button on the PRANS console.
7. The PRANS system uses the coordinates of the initialization point to automatically determine the relative range and bearing to each of the radar targets and sets up the system to operate using those targets. Output data is generated within two revolutions of the radar antenna (approximately five seconds).
8. The PRANS console displays the distance in feet to the desired buoy position as measured along the Y axis (it is assumed that the Y axis is parallel to the centerline of the channel for this example).
9. The PRANS console displays the speed of the vessel along the Y axis.
10. The PRANS console displays the offset distance from the Y axis in feet (measured along the X axis).
11. The Conning officer uses the displayed information to maneuver the buoy tender, with the objective of making all of the information displays read zero. When this is accomplished, the selected chain stopper will be located directly over the desired buoy anchor position, and the vessel will be stopped relative to the bottom.

NOTE

This example illustrates only one of several different methods that can be employed for buoy positioning operations.

Format for Information Display

The above example cited one possible type of information display format. Another method might involve cataloging the buoy positions relative to the centerline of the channel. Knowing that C"1" should be located 8,000 feet from the end of the channel, and 270 feet from the center of the channel, the conning officer can maneuver the vessel to achieve these coordinates on the PRANS display. The information in this case would be generated relative to the centerline of the channel.

The most meaningful format can only be developed after consultation with conning officers with extensive experience in buoy positioning operations. It is recommended that their opinions be obtained through direct interviews, or through the use of a questionnaire. The two examples provided here could be cited as possible candidates, and space provided for other suggestions.

*Estimated Cost of Instrumenting a Buoy Tender

The estimated cost of implementing a PRANS system, interfaced with an AN/SPS-64 (V) radar aboard a buoy tender is $15,000 to $17,000. This estimate includes all interfacial hardware and cables, but does not include the cost of labor involved in making the installation.

The estimate of cost includes an information display designed expressly for buoy positioning operations, and all necessary equipment modifications to the radar set for compatibility.

Summary of Alterations to the AN/SPS-64(V) to Effect Integration

1. Installation of optical shaft encoder for antenna position determination.
2. Installation of means to take out raw video signals prior to filtering.
3. Installation of means to inhibit STC function to permit a small amount of the transmitted pulse to "leak" through the receiver.
4. Installation of a means to sample the modulator trigger for circuit arming purposes.
5. Installation of a STERN MARKER switch, or conversion of the HEADING MARKER to STERN MARKER if found appropriate.
6. Installation of means to control the pulse width and repetition frequency.
7. Installation of means to insert bracket information on the PPI.

Conclusions

The AN/SPS-64(V) radar set can be successfully interfaced to the PRANS system to provide maneuvering information for buoy positioning operations. The information will be generated automatically after the system is initialized and started by the conning officer. The position information will be accurate to a maximum of five (5) feet r.m.s. error.

The integrated system will facilitate the training of conning officers for buoy tenders. Cost savings may be realized through the use of the integrated system by reducing the amount of maneuvering necessary to accurately position a floating aid. Buoy positioning operations may be performed during periods of low visibility, which now prevent the use of horizontal sextant angles for positioning.

*Cost is based on 25 systems and does not include non-recurring expenses for special design requirements or display design.

Recommendations

It is recommended that a survey be taken of past and present buoy tender conning officers to determine the optimum information format for buoy positioning operations.

It is also recommended that the desired position of buoy anchors be converted to the state plane coordinate system for compatibility with dredging operations.

REFERENCES

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4. Robertson, Sloan D., "Targets for Microwave Radar Navigation," Bell System Technical Journal, Oct. 1947, p.852.

5. Skolnik, op cit, p.1-4.

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7. Hill, J.C.,II, Dutton's Navigation and Piloting, U.S. Naval Institute, Annapolis, 1958, Appendix O, p.742.

APPENDIX A

PRANS Technical Summary

and

Theory of Operation

PRANS TECHNICAL SUMMARY

The system automatically provides a near real time navigational information. It is computer controlled and does not require manual operations after an initial starting procedure.

An X-band radar mounted on the vessel sends out a series of short pulses to retro-reflectors, mounted on structures located along channels or waterways at known survey points.

The time required for the pulse to travel to the target and return to the microwave receiver is a measurement of the range to the target. To achieve the accuracies necessary to maintain the system specifications, the transit time of the r.f. pulses are measured with accuracies under a nanosecond by an ultra-high resolution interval timer.

The interval timer determines the two ranges from inputs provided by the microwave ranging subsystem. These ranges are utilized by the computer to calculate the solution of the trigonometric problem in deriving the navigational information which is displayed digitally.

The system is placed in operation when the vessel approaches approximately within 1000 feet of a pre-determined point. The computer determines the ranging points from data contained in the program, sets up the interval timer for measuring the interval between the transmitted and received signals of the microwave ranging subsystem and provides the solution of the problem to the display unit. The system continuously measures and computes solutions and up-dates the display.

This navigation system has the following characteristics:

1. Automatic operation after initial starting procedure
2. Weather and light conditions independent
3. Continuously up-dated positional information at frequent intervals (approaching real time)
4. Display format related to the specific situation of the vessel relative to the intended course

The display unit provides the following data:

1. Displacement from the intended track (feet, right or left)
2. Distance to way point (feet)
3. Attitude relative to the intended track(angular difference between the vessel's heading and the azimuth angle of the track

4. Vessel speed

To generate positional information the system precisely measures the range from the ship to two discrete radar targets on the shore. The exact locations of the radar targets and the relative position of the channel with respect to the two targets are included in the computer program. The computer performs the geometrical calculations to provide the solution to the problem. All measurements and calculations are performed by the shipboard equipment. The shore based radar targets are completely passive.

When the vessel reaches a way point, an indication is provided and the navigational information becomes relative to a follow on course. As the vessel changes course the system indicates h* relative to the new course. The system will provide an indication of arrival at a pre-determined point at the conclusion of all prescribed maneuvers.

The choice of utilizing shipboard electronic equipment and passive retro-reflectors was based on several important factors:

(1) Passive Retro-reflectors:

a) Require no electrical power
b) Are inexpensive
c) Require minimal maintenance

(2) Electronic malfunctions only effect the operation of the vessel in which the malfunctions occur.

(3) Maintaining all electronics onboard simplifies the system. In effect, the system, made up of the following assemblies, provides automated radar navigation:

a) Range determination (radar and interval timer)
b) Data processing and control (computer and controls)
c) Display (display console)

* h = distance to centerline

To generate positional information the system precisely measures the range from the ship to two discrete radar targets on the shore. The exact location of the radar targets is included in the computer program, as well as the relative position of the channel with respect to the two targets. The computer performs the geometrical calculations to provide the solution to the problem. All measurements and calculations are performed by the shipboard equipment, and the shore based radar targets are completely passive.

Figure 1 illustrates the parameters associated with the geometry of the channel relative to the retro-reflectors. Similar geometrical parameters are stored in the computer memory for each channel in the waterway (in numerous instances one set of retro-reflectors will serve two or more channels).

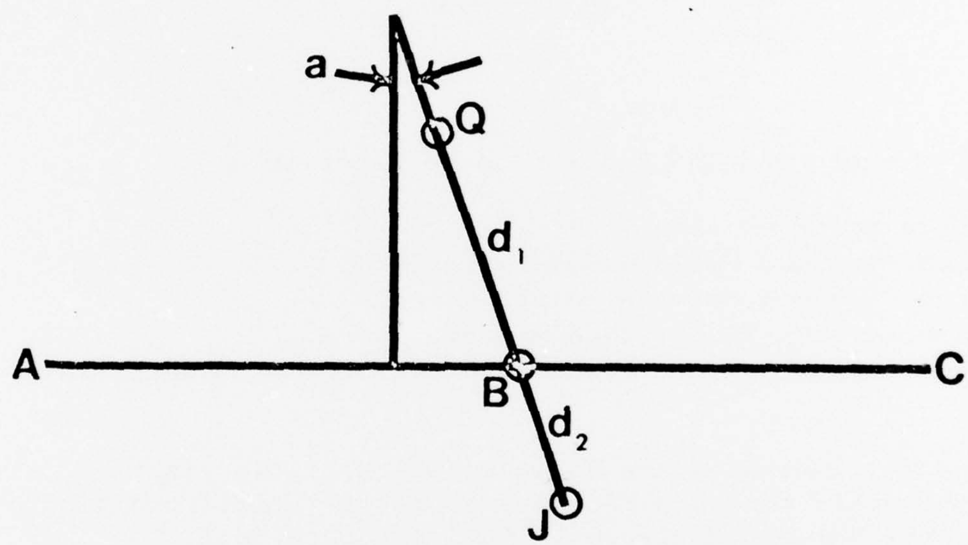

Figure 1

Channel Geometry Data Stored in Computer Memory

ABC: Centerline of channel
J: Retro-reflector location
Q: Retro-reflector location
B: Intersection of channel centerline and line JQ
a: Angle between line JQ and a line perpendicular to ABC
d_1: Distance between points B and Q
d_2: Distance between points B and J

Figure 2 illustrates the two range measurements made by the system, and the information that is to be determined. The distance d_3 is adjusted by the computer to reflect the distance from point B to the actual turning point at the end of the channel.

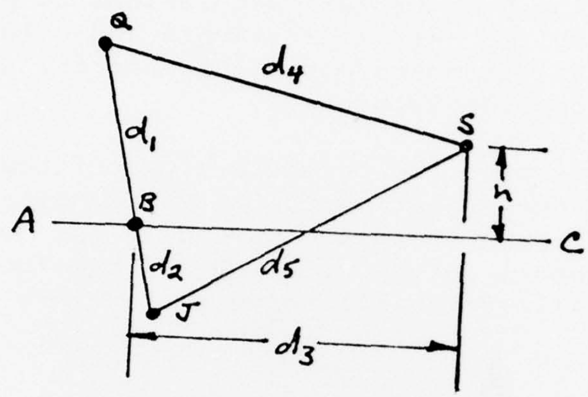

Figure 2

Measured Distances and Information to be Determined

S: Reference point on ship

d_4: Measured distance between points S and Q

d_5: Measured distance between points S and J

d_3: Distance to turn (To be determined)

h: Distance from S to the channel centerline (to be determined)

Figure 3 illustrates the basic solution of two right triangles to yield the required parameters of lateral position in the channel (h) and distance to the next turn (d_3).

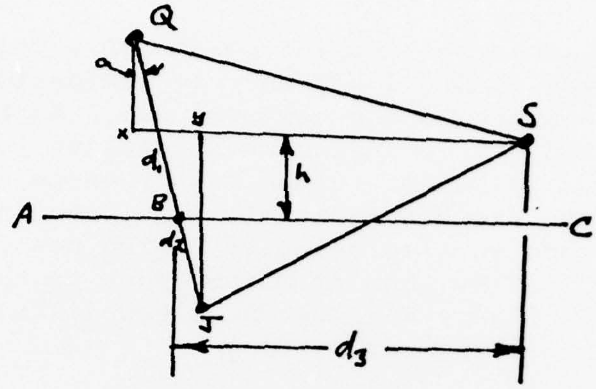

Figure 3

Method of Solution for h and d_3

From right triangle SYJ:

Distance between points J and Y = $(d_2)\ (\cos a) + h$

Distance between points S and Y = $d_3 - (d_2)\ (\sin a)$

Yielding:

(A) $$(d_5)^2 = \left[(d_2)\ (\cos a) + h\right]^2 + \left[d_3 - (d_2)\ (\sin a)\right]^2$$

From right triangle SXQ

Distance between points Z and X = $(d_1)\ (\cos a) - h$

Distance between points S and X = $d_3 + (d_1)\ (\sin a)$

Yielding:

(B) $$(d_4)^2 = \left[(d_1)\ (\cos a) - h\right]^2 + \left[d_3 + (d_1)\ (\sin a)\right]^2$$

(A) and (B) provide solutions for d_3 and h for every d_4 and d_5.

(Two equations in two unknowns)

A determination of h and d_3 is made every 2-4 seconds automatically, and the change in d_3 relative to time is integrated to determine the speed of the vessel.

When the vessel reaches the turning point for a course alteration, an indication is provided, and the navigational information becomes relative to the next channel. As the vessel changes course the system indicates h relative to the new channel to provide information to the master as to the position of the vessel in the next channel. The crab angle indication during the turn is also relative to the new channel, and provides a decreasing angular measurement to the completion of the turn. Figure 4 illustrates how distance h is generated during the turning maneuver.

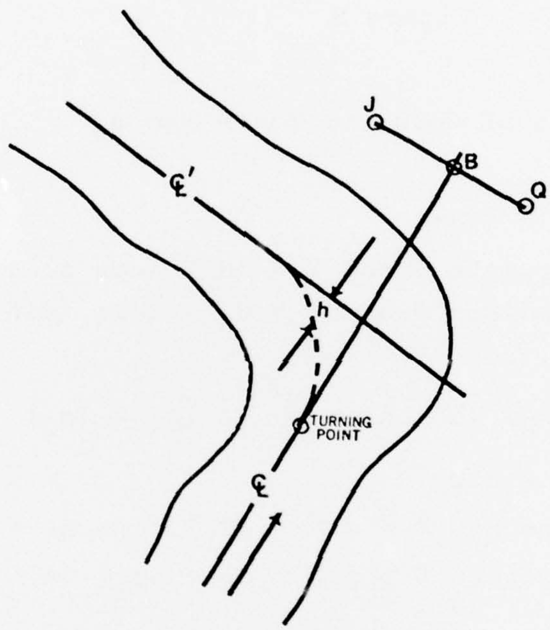

Figure 4

Distance h Relative to Next Channel at Turning Point

Figure 5 illustrates the relationship of the turning points to the centerline intersections for three consecutive channels.

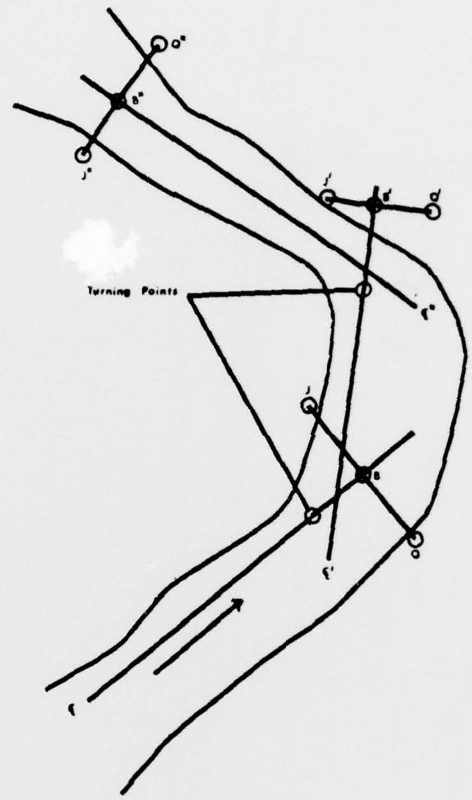

Figure 5

Relationship of Turning Points to Intersects

Some Basic Decisions Regarding this Approach

The choice of utilizing shipboard electronic equipment and shore based passive retro-reflectors was based on several important factors:

(1) Shore Based Passive Retro-reflectors:
    Require no electrical power
    Are easily implemented
    Are inexpensive
    Require minimal maintenance

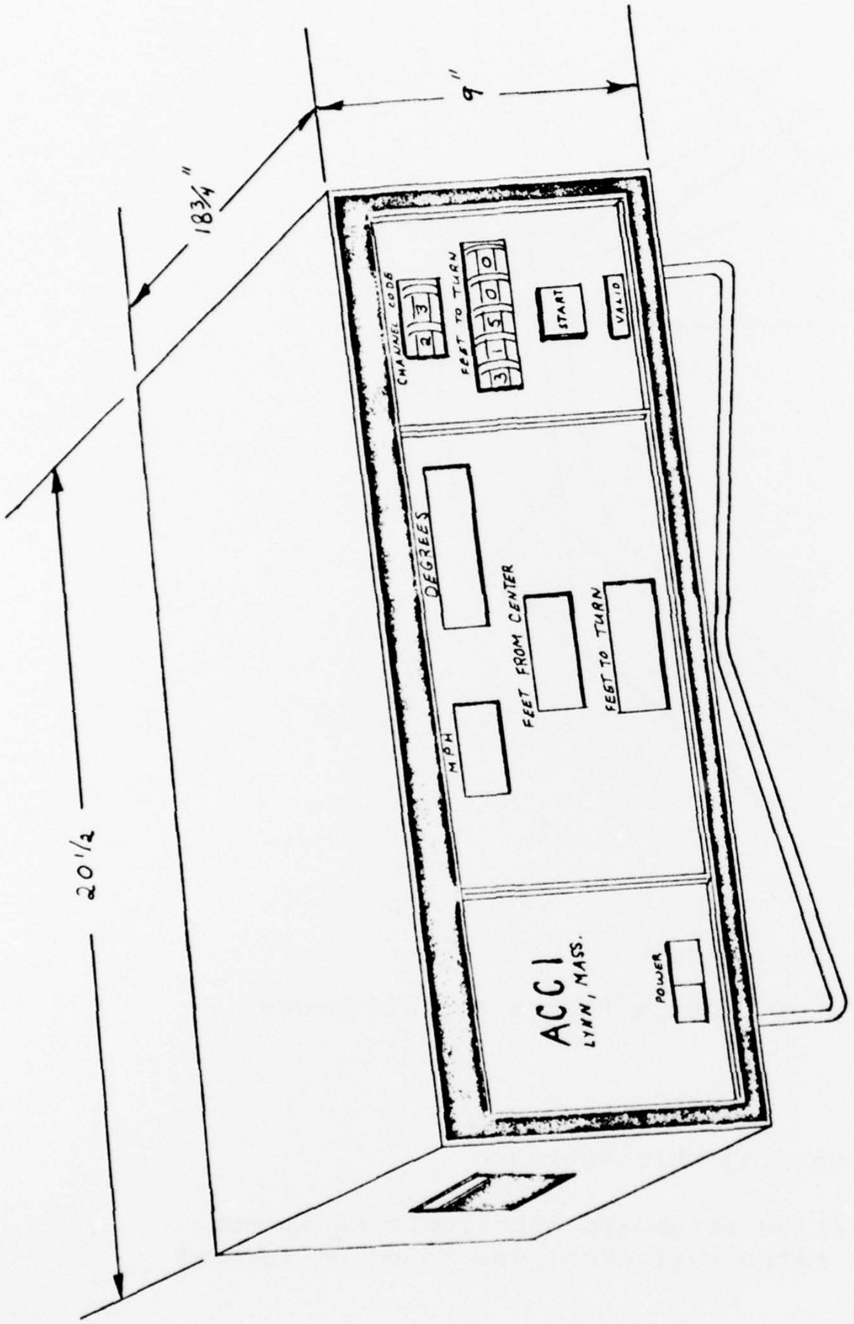
9"
18¾"
20½
CHANNEL CODE
2 3
FEET TO TURN
3 1 5 0 0
START
VALID
DEGREES
FEET FROM CENTER
FEET TO TURN
MPH
ACCI
LYNN, MASS.
POWER

Figure 6

APPENDIX B

Expected Performance in the Presence Of Radar Clutter

The radar cross section (R.C.S.) of a retro-reflector must be sufficiently large to assure that the radar return from the retro-reflector is much larger than the return from other radar targets in the vicinity of the retro. Additionally, the R.C.S. must be large to assure that a sufficiently large signal is maintained at the radar receiver to provide adequate measurement levels at the maximum range of the system. In most situations, if the first of these two requirements is satisfied,the minimum signal level will,as a matter of course, be satisfied. In the selection of sites for retro-reflector locations,attention is directed to avoidance of areas of strong radar targets, such as cliffs or large metal or stone

structures. Retro-reflectors can be implemented to exceed the radar cross sections of most of the natural terrain found along rivers. To illustrate, a tri-hedral retro-reflector, three feet on a side, would present a radar target more than seventy times larger than an island fifty feet in diameter and ten feet high, for normal marine radars (3,253 square meters vs. 46.5 square meters).

The extent of the radar cross section of the environment surrounding the retro-reflector is a function of the antenna characteristics of the radar, the ranging increments of the radar (range gates), and the microwave reflectivity of the terrain. In order to satisfy the requirements of the signal processor, the ratio of the radar cross section of the retro-reflector to the radar cross section of the "clutter" should be between 60 to 100 to 1 (60/1 to 100/1), or 18-20 db (power ratio).

To keep the units of radar cross section in more manageable terms, they are usually expressed in decibels relative to a square meter (power ratio; 10 times the logarithm to the base ten of the radar cross section in square meters). In this manner, a radar cross section of 22,910 square meters can be expressed as 43.6 db re m^2. This method permits a

practical evaluation of retro-reflector size to overcome clutter by adding 18-20 db to the radar cross section of the clutter to derive the necessary retro-reflector radar cross section.

The radar cross section of the clutter is largest at the longest range from the retro-reflector. This is due to the characteristics of the radar antenna. Thus, the radar cross section of the retro-reflector must be determined to provide adequate margin over the clutter at the maximum range that retro-reflector is to be used. Conveniently, this factor acts in the same manner as the change in signal-to-noise ratio in the receiver of the radar. That is, as range decreases, the ratio of retro-reflector to clutter radar cross section, and the signal-to-noise ratios both improve.

This is corroborated by a review of a representative set of clutter measurements.

σ_c	for clutivated terrain:	-20 to -35 db
σ_c	for trees:	-15 to -20 db
σ_c	for forest, median return:	-40 db
σ_c	for peak value, high clutter median return:	-50 db
σ	exceeded only 5% of the time:	-20 db

Based on this sampling of the measurements, we shall use a value

$$\sigma_c = -20 \text{ db or } 0.01 \text{ m}^2/\text{m}^2$$

The radar cross section of clutter was calculated as follows:

Using the range cell approach for low grazing angles, the effective area of illuminated clutter can be determined from the given antenna characteristics. The effective area is multiplied by the clutter reflectivity to derive the radar cross section.

$$A_{eff} = \frac{\theta_a R}{2} \times \frac{\tilde{\tau} C}{2} \times \frac{1}{\cos E}$$

where:

A_{eff} = effective area of illuminated clutter

θ_a = horizontal beam width of the antenna (in radians)

R = range (in meters)

τ = .05 nsec - 5 x 10^{-8} seconds (range cell)

C = speed of light (2.997925 x 10^8 meters per second)

E = grazing angle

cosE = 1 or nearly so

Reflectivity of "clutter" is related to wavelength as follows:

$$\sigma_o = \frac{.00032}{\lambda}$$

For X-band, λ = 3.2 cm, and σ_o = .01

Therefore the radar cross section of the clutter is:

$(A_{eff}) \times (\sigma_o)$ = R.C.S.

The radar cross section of clutter for the AN/SPS-64 radar at a maximum range of 10 N.M. (18.5 kilometers) is calculated as follows:

$$A_{eff} = \frac{(2.09439 \times 10^{-2} \text{ radians})(1.85 \times 10^{4} \text{ meters})}{2} \times \frac{\tau c}{2} \times \frac{1}{\cos e}$$

A_{eff} = 1452 square meters

Radar cross section = 14.52 square meters, or 11.6 db re m^2

In the radar analysis contained in the text of this report, the resultant signal-to-noise ratios from the use of two different radar targets were derived. For the larger of the two targets, the radar cross section was determined to be 42.9 db/m^2, and the signal-to-noise ratio was calculated to be 18.7 db. Since the radar cross section of the reflector is more than 31 db greater than that of the clutter, the radar return from the clutter will be below the noise level and minimum discernable signal level of the receiver. The same is true for the smaller of the two reflectors, where the radar cross section of the reflector is more than 21 db greater than clutter.